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Trade-offs in using European forests to meet climate objectives

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The Paris Agreement promotes forest management as a pathway towards halting climate warming through the reduction of carbon dioxide (CO_2) emissions[1]. However, the climate benefits from carbon sequestration through forest management may be reinforced, counteracted or even offset by concurrent management-induced changes in surface albedo, land-surface roughness, emissions of biogenic volatile organic compounds, transpiration and sensible heat flux[2–4]. Consequently, forest management could offset CO_2 emissions without halting global temperature rise. It therefore remains to be confirmed whether commonly proposed sustainable European forest-management portfolios would comply with the Paris Agreement—that is, whether they can reduce the growth rate of atmospheric CO_2, reduce the radiative imbalance at the top of the atmosphere, and neither increase the near-surface air temperature nor decrease precipitation by the end of the twenty-first century. Here we show that the portfolio made up of management systems that locally maximize the carbon sink through carbon sequestration, wood use and product and energy substitution reduces the growth rate of atmospheric CO_2, but does not meet any of the other criteria. The portfolios that maximize the carbon sink or forest albedo pass only one—different in each case—criterion. Managing the European forests with the objective of reducing near-surface air temperature, on the other hand, will also reduce the atmospheric CO_2 growth rate, thus meeting two of the four criteria. Trade-off are thus unavoidable when using European forests to meet climate objectives. Furthermore, our results demonstrate that if present-day forest cover is sustained, the additional climate benefits achieved through forest management would be modest and local, rather than global. On the basis of these findings, we argue that Europe should not rely on forest management to mitigate climate change. The modest climate effects from changes in forest management imply, however, that if adaptation to future climate were to require large-scale changes in species composition and silvicultural systems over Europe[5,6], the forests could be adapted to climate change with neither positive nor negative climate effects.

Following the Paris Agreement, the European Union and its 28 member states have committed to a 40% domestic reduction in greenhouse-gas emissions compared to 1990 levels by 2030. About 99% of this reduction is expected to come from emission reductions and the remaining 1% from land use, land-use change and forestry[7]. The commitment to reduce domestic greenhouse-gas emissions through forestry is in turn reflected in the national strategies of several European countries for energy, climate change and forestry[8–10]. These strategies typically focus on enhancing forestry-based sinks and reservoirs and developing neutral- or negative-emission approaches based on woody biomass. Furthermore, European forest owners who have reported to have experienced climate change have indicated that this experience influenced their management decisions[11]. Hence, climate change and the Paris Agreement are already shaping forest-management decisions. Despite being explicitly mentioned in both the Kyoto Protocol[12] and the Paris Agreement[1], little is known about the climate effects of forest management, including the effects of human-induced changes in tree species and silvicultural systems[3,13,14].

This study searches for spatially explicit forest-management portfolios for Europe that comply with the Paris Agreement up to the turn of the twenty-first century. The agreement requires that forest management jointly reduces the growth rate of atmospheric CO_2 (Articles 4 and 5) and the radiative imbalance at the top of the atmosphere (Article 2). Furthermore, forest management compliant with the Paris Agreement should neither increase the near-surface air temperature (hereafter referred to as 'air temperature') nor decrease precipitation, because changing the climate of the terrestrial biosphere would make adaptation to climate change (Article 7) even more difficult (see Supplementary Information, 'Operationalizing the Paris Agreement').

Simulation experiments that combine vegetation modelling, climate modelling, vegetation–climate feedbacks and life-cycle analysis are used to quantify the CO_2 emissions, radiative imbalance at the top of the atmosphere, air temperature and precipitation of three spatially explicit forest-management portfolios for Europe (Extended Data Fig. 1). Each portfolio has a distinct objective: maximize the forest carbon sink, maximize forest albedo or reduce air temperature.

All portfolios start from the same 2010 species and age–class distribution. Once an individual forest reaches maturity, six scenarios are explored: (i) refrain from harvesting; (ii) harvest, replant the same species and apply the same silvicultural system as before; (iii) harvest, replant the same species and thin before the final felling; (iv) harvest, change to the most common deciduous species in that region and thin before the final felling; (v) harvest, change to the most common deciduous species in that region and manage it as a coppice; and (vi) harvest, change to the most common conifer species in that region and thin before the final felling. Subsequently, portfolios are constructed by selecting the best-performing management scenario for each of the three objectives and for each $0.5° \times 0.5°$ grid cell in the European domain.

In contrast to previous land-use simulation experiments, our portfolios simulate a realistic rate of change for tree-species distributions and silvicultural systems because changes are only implemented following a harvest or stand-replacing mortality. Thus, management changes are dictated by forest growth and human choices within natural constraints, rather than through externally prescribed harvest volumes or through strictly natural succession.

A management portfolio that maximizes the carbon sink[15,16] reflects the widely held view that the net climate effect of forest management is dominated by decreasing the growth rate of atmospheric CO_2 through forest-based carbon sequestration, carbon storage in wood products, and material and energy substitution. Implementing the sink-maximizing portfolio—instead of the business-as-usual one—would require converting 475,000 km^2 of deciduous forest in central and southern Europe

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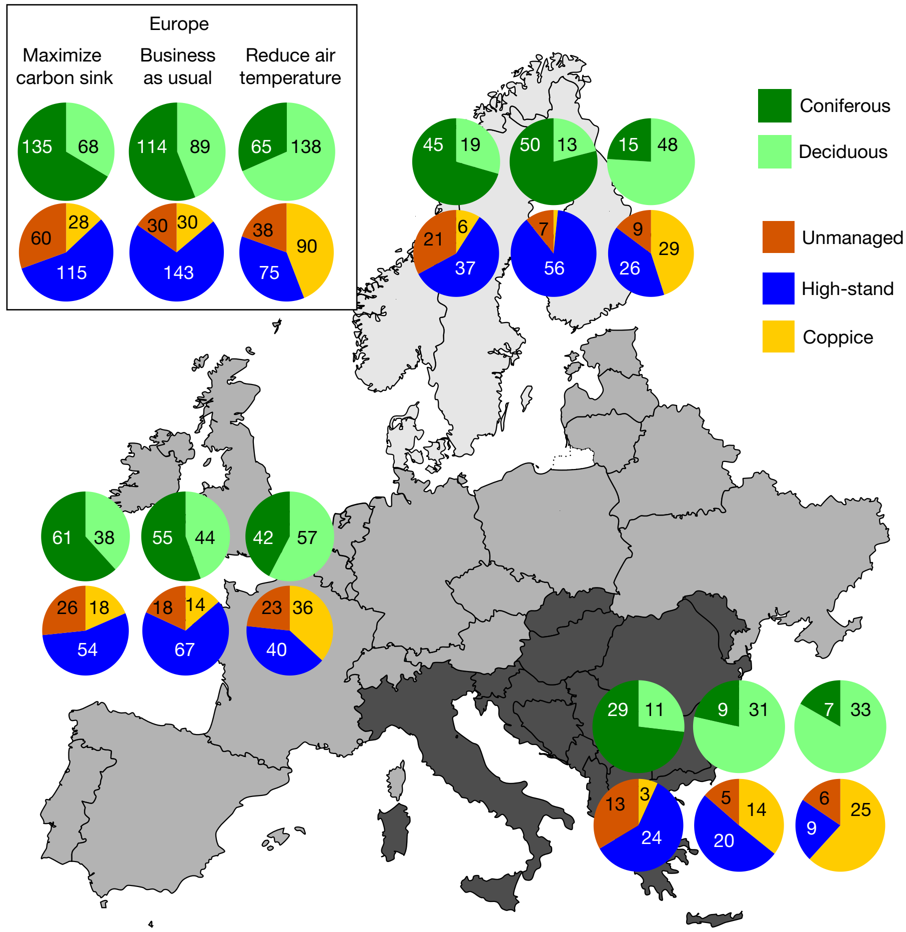

Fig. 1 | Forest surface areas ($\times$10,000 km^2) by 2100 under different forest-management portfolios. The portfolios considered here maximize the carbon sink, extend present-day management (business as usual) and reduce the air temperature. Forest management approaches include changes in tree species composition and silvicultural systems. The inset presents the mean values for all of Europe. Regional differences are shown for three geographical regions, each shown in a different shade of grey.

into coniferous forest, whereas 266,000 km^2 of previously coniferous forests in northern and central Europe would have to be converted to deciduous forests (Fig. 1; Extended Data Table 1; see Supplementary Information, 'Drivers of changes in forest management').

A sink-maximizing portfolio would come with a 12% lower wood harvest but could offset an additional 8.1 Pg C (1 Pg $=10^{15}$ g) of fossil-fuel emissions (Table 1) between 2010 and 2100 compared with a business-as-usual management portfolio, which extends the present-day forest-management portfolio into the future. This increase in the projected carbon savings is similar to estimates reported by the forestry sector[16] and could be achieved by optimizing the balance between forest-based sequestration (8.2 Pg C) on the one hand and product-based sinks and substitution (-0.3 Pg C), energy-based substitution (0.2 Pg C) and savings in the emissions from forest exploitation, wood processing and product manufacturing (0.05 Pg C) on the other. Accounting for ocean uptake of atmospheric CO_2 (see Supplementary Information, 'Life cycle analysis') results in a cumulated net reduction of the atmospheric CO_2 concentration of 4.3 Pg C in 2100, which translates into a 2 p.p.m. decrease in atmospheric CO_2 compared with the business-as-usual portfolio (Table 1). Owing to the changes in tree species and silvicultural systems that are required to realize this 2 p.p.m. reduction, the approximately 0.002 W m^{-2} decrease in the radiative imbalance at the top of the atmosphere from the stronger carbon sink[17] is neutralized by unintended, but unavoidable, changes in surface albedo (-0.001) and cloud cover (-0.1%). The carbon-sink-maximizing portfolio has a small negative effect on annual precipitation (-2 mm) and no effect on air temperature (Table 1).

A temperature-based portfolio reflects the idea that management-induced changes in surface properties may redistribute heat away from the land surface, resulting in a local cooling of the land surface[18] that can be beneficial for organisms living there. Implementing such a portfolio requires converting 493,000 km^2 of coniferous forests to deciduous forests (of which 65% would be in Scandinavia) and coppicing an additional 600,000 km^2 of deciduous forests (Fig. 1; Extended Data Table 1; see Supplementary Information, 'Drivers of changes in forest management'). Such changes in forest management would, however, reduce the wood harvest by 25% compared to the business-as-usual portfolio (Table 1). By 2100 these changes would result in a cumulative net reduction of the atmospheric CO_2 concentration of 1.8 Pg C, which is equivalent to a 0.9 p.p.m. reduction of atmospheric CO_2 compared with the business-as-usual portfolio (Table 1).

The combined biogeochemical and biophysical effects of this portfolio come without a significant effect on the radiative imbalance at the top of the atmosphere (one-sided t-test, $P=0.28$), but could contribute to a 0.3 K cooling over Scandinavia, with a much smaller effect on temperature over the rest of Europe (Fig. 2a). Following a large-scale transition to deciduous species, cooling of the air temperature is projected to occur only in winter and spring (Extended Data Fig. 2). In spring, air-temperature cooling from an increase in surface albedo due to decreased snow masking by deciduous canopies would be partly compensated by warming from a decrease in turbulent fluxes caused by the absence of leaves until bud break later in spring (Fig. 2b). Our simulation experiment thus confirms the role of transpiration in determining air temperature, even at high latitudes[19].

A portfolio that maximizes the albedo[20] reflects the view that managing the forest albedo would reduce the radiative imbalance at the top of the atmosphere while maintaining the forest carbon sink.

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Table 1 | Biogeochemical and biophysical effects over Europe in 2100 for four different forest-management portfolios

Variable (units)	Business as usual	Maximize carbon sink	Maximize albedo	Reduce air temperature
Global average TOA ($W m^{-2}$)	4.31 ± 0.01	4.31	4.33	4.32
Change in CO_2 sink and avoided emissions between 2010 and 2100 (Pg C)	4.7	12.8	5.0	8.1
Change in net cumulated atmospheric CO_2 between 2010 and 2100 (Pg C)	−2.7	−7.0	−2.8	−4.5
Atmospheric CO_2 (p.p.m.)	934.6	932.6	934.6	933.8
Air temperature (K)	283.84 ± 0.001[a]	283.84	283.83	283.81
Annual precipitation (mm)	734.7 ± 0.1	732.6	730.0	730.9
Summer precipitation (mm)	166.1 ± 0.1	165.2	163.7	165.0
Wood harvest ($Tg C y^{-1}$)	203.2	179.5	144.5	151.6
Surface albedo (–)	0.113 ± 0.0001[a]	0.113	0.128	0.126
Evapotranspiration (mm)	555.5 ± 0.1	552.8	546.4	549.2
Latent heat ($W m^{-2}$)	44.35 ± 0.01[a]	44.13	43.60	43.82
Sensible heat ($W m^{-2}$)	26.67 ± 0.01[a]	26.82	27.28	27.00
Total cloud cover (%)	46.8 ± 0.1[a]	46.7	46.7	46.6

The business-as-usual simulation, which served as a control, was repeated three times with slightly different initial atmospheric conditions (see Supplementary Information, 'Equilibrium climate for the management portfolios'). The variability between these three repetitions was considered to be the minimal model noise of the climate model and to define one standard deviation. TOA denotes the radiative imbalance at the top of the atmosphere. Results for two additional portfolios are presented in Extended Data Table 2.
[a]Upper limit.

Our simulations confirm that an albedo-maximizing portfolio would decrease wood harvest by 30% and realize cumulated net emission savings of up to 2.8 Pg C, which is comparable to the savings expected from the business-as-usual portfolio. However, the increase in surface albedo that can be realized through the albedo-based portfolio (+0.015) would be compensated by a decrease in cloud cover (−0.1%) and therefore come without a significant effect on the radiative imbalance at the top of the atmosphere (one-sided t-test, $P = 0.07$) and with a small negative effect on air temperature (−0.01 K; Table 1).

Furthermore, all portfolios reduce the mean annual precipitation by 2.1–4.7 mm compared to the business-as-usual portfolio. Reductions are evenly spread across the seasons and consistent with the decrease in cloud cover and evapotranspiration (Table 1). Hence, none of the tested forest-management portfolios meets all of the four criteria set for compliance with the Paris Agreement. Maximizing the carbon sink and maximizing the forest albedo both meet one of the four criteria. Managing European forests with the objective of reducing air temperature satisfies two of the four criteria: reducing the air temperature and reducing the CO_2 growth rate. Therefore, making trade-offs seems unavoidable when using European forests to meet climate objectives.

To our knowledge, this study is the first to quantify the capacity of forest management to comply with the Paris Agreement while addressing both biogeochemical and biophysical effects; hence, its results could not be compared with previous reports. The small temperature effects, compared with those found in global afforestation and deforestation studies[21–24], are thought to be the consequence of considering a realistic 90-year period of management changes and testing the portfolios for a limited global land area, that is, about 7% of the global total of managed forest[14]. Although a global implementation of carbon-based forest management will probably enhance the carbon sink of the forest sector globally[15], the combined biogeochemical and biophysical effects cannot be extrapolated from Europe to the global scale owing to biome-specific land–atmosphere interactions[25,26].

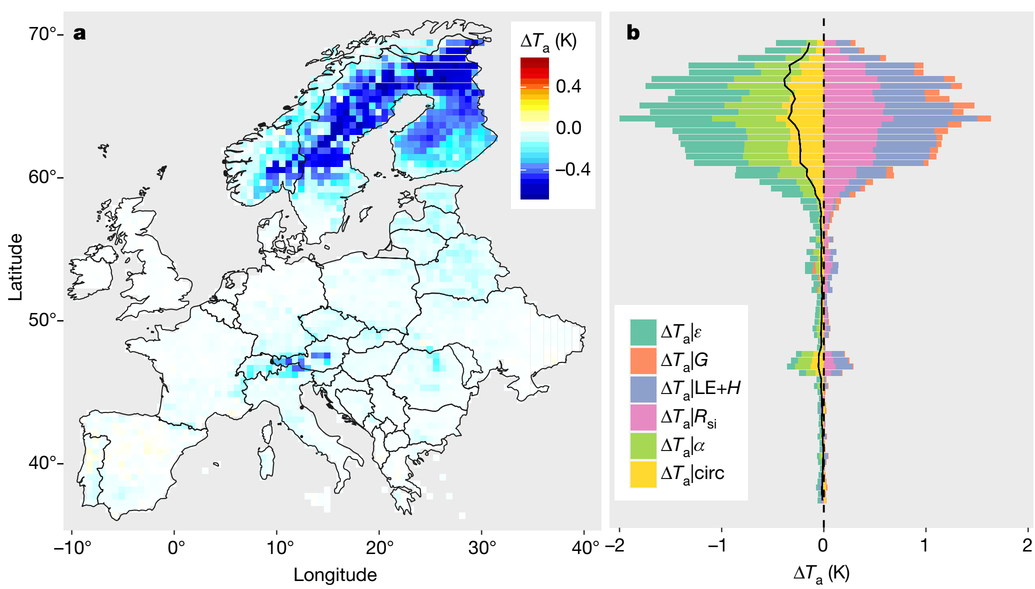

Fig. 2 | Changes and main drivers of air temperature in February and March by the turn of the 21st century for a forest-management portfolio that reduces the near-surface air temperature. a, Spatially explicit changes in air temperature (ΔT_a) in February and March. Temperature changes smaller than 1.96σ are shown in white, where the standard deviation σ represents the minimal noise of the simulation code LMDzORCAN (see Supplementary Information, 'Equilibrium climate for the management portfolios'). **b**, Drivers of the changes in springtime air temperature for 0.5° latitudinal bands. Shown are air temperature changes due to changes in atmospheric emissivity ($\Delta T_a|\varepsilon$), ground heat flux ($\Delta T_a|G$), turbulent fluxes ($\Delta T_a|\mathrm{LE}+H$), shortwave incoming radiation ($\Delta T_a|R_{si}$), which in this simulation experiment is a proxy for cloud cover, surface albedo ($\Delta T_a|\alpha$) and atmospheric circulation ($\Delta T_a|\mathrm{circ}$). See Supplementary Information for details.

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A global implementation of locally optimized forest-management portfolios would lead to larger areas with near-surface cooling. Given that air temperature cooling was found to saturate quickly with the fractional change in tree species composition (Extended Data Fig. 3), the magnitude of the cooling is not expected to change substantially following a large-scale implementation, unless ocean feedbacks[19,22], cloud feedbacks through species-specific biogenic emissions of volatile organic compounds[27], and changes in the North Atlantic Oscillation[28], which were not fully accounted for in this study, are among the key drivers.

Our results demonstrate that, on the basis of a single model, in the absence of carbon capture and storage the additional climate benefits of sustainable forest management will be modest and local rather than global. Hence, we suggest that the primary role of forest management in Europe in the coming decades is not to protect the climate, but to adapt the forest cover to future climate[5] in order to sustain the provision of wood and ecological, social and cultural services[29], while avoiding positive climate feedbacks from fire, wind, pests and drought disturbances[30]. Even if adaptation would require large-scale changes in the tree species composition and silvicultural systems over Europe[5,6], our results imply that these changes themselves will probably have little impact on the climate.

Code availability

The code and the run environment used in this study are open-source and distributed under the CeCILL (CEA CNRS INRIA Logiciel Libre) license. The codes of ORCHIDEE-CAN_r2290 and ORCHIDEE-CAN_r3069 can be accessed at https://doi.org/10.14768/06337394-73A9-407C-9997-0E380DAC5595 and https://doi.org/10.14768/06337394-73A9-407C-9997-0E380DAC5596, respectively. Access to the run environment and LMDzORCAN are restricted to registered users; requests can be sent to the corresponding author. The post-processing code used to estimate the life-cycle sinks and emissions of the forestry sector (see Supplementary Information, 'Life cycle analysis'), search for the optimized management portfolios (see Supplementary Information, 'Management optimization' and decompose the air temperature into its main drivers (see Supplementary Information, 'Decomposing near-surface air temperature') can be accessed at https://doi.org/10.5281/zenodo.1284533.

Data availability

Figures 1, 2, Table 1, Extended Data Figs. 2, 3, Supplementary Fig. 1 and Extended Data Table 1, 2 are based on a simulation experiment whose output files (about 7.4 Tb) will be provided upon reasonable request. The data files that were used to set the boundary conditions of ORCHIDEE-CAN and LMDzORCAN (about 70 Gb) will be provided upon reasonable request.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, statements of data availability and associated accession codes are available at https://doi.org/10.1038/s41586-018-0577-1.

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Author contributions S.L. and M.J.M. designed the study. M.J.M., J.O., J.R., Y.-Y.C., K.N., A.V. and S.L. developed, parameterized and validated ORCHIDEE-CAN. G.M., M.J.M., J.G. and S.L. conducted the simulation experiment. S.N.D. developed the life-cycle analysis method. G.M., Y.-Y.C. and S.L. analysed the data. G.M., M.J.M., J.O., J.R., Y.-Y.C., K.N., A.V., A.S.L. and S.L. contributed to the interpretation of the results.

Competing interests The authors declare no competing interests.

Additional information
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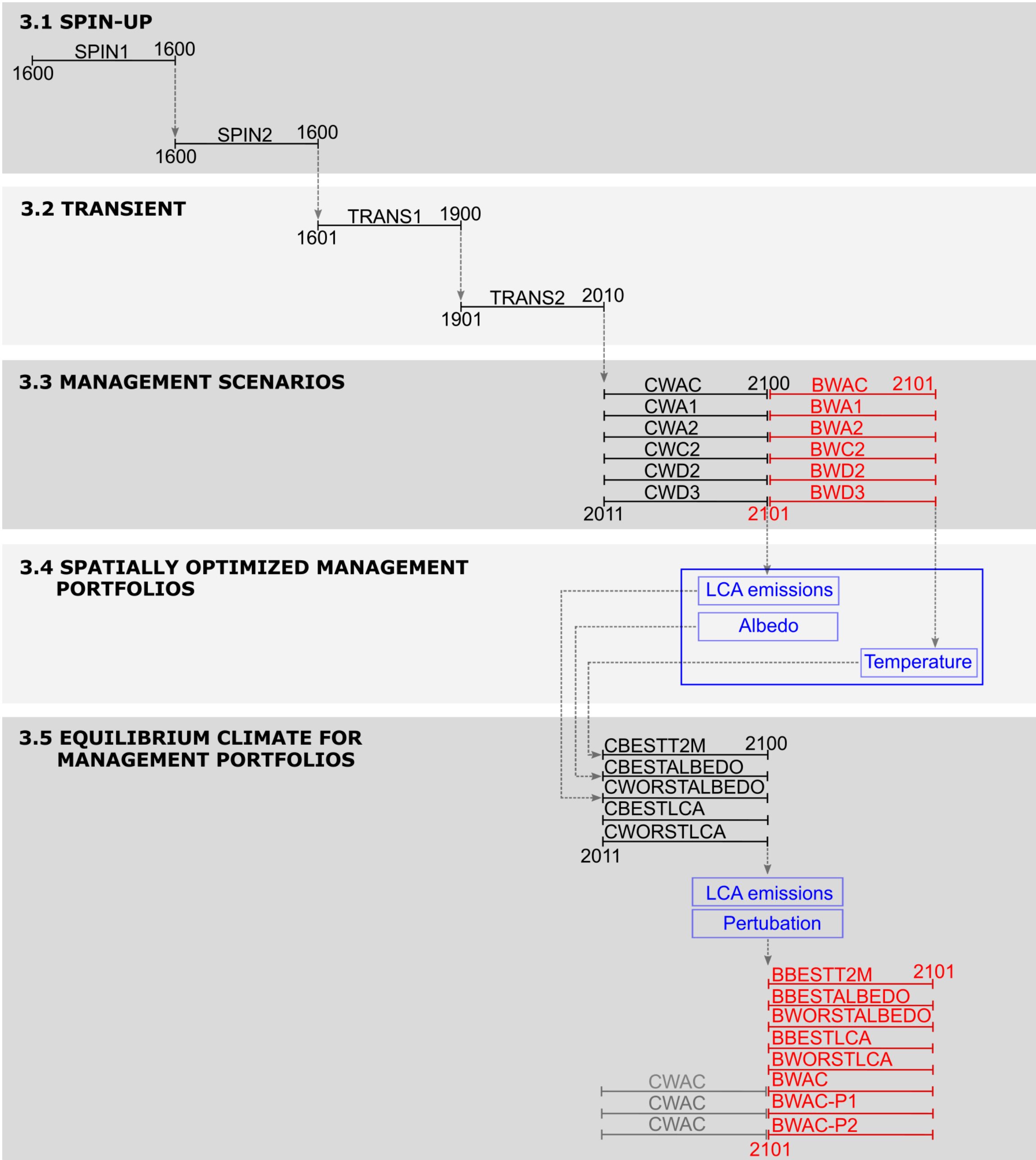

Extended Data Fig. 1 | Setup of the simulation experiments. The experiments are described in the section 'Simulation experiment' in Supplementary Information. Simulations with ORCHIDEE-CAN are shown in black and simulations with LMDzORCAN are shown in red. Blue boxes denote intermediate calculations using the simulation results (see Supplementary Information, 'Spatially optimized management portfolios' and 'Equilibrium climate for the management portfolios'). The simulations shown in this figure correspond to runs with reduced air temperature (BBESTT2M), maximized surface albedo (BESTALBEDO), minimized surface albedo (BWORSTALBEDO), maximized carbon sink (BBESTLCA), minimized carbon sink (BWORSTLCA) and business as usual (BWAC). BWAC, BWAC-P1 and BWAC-P2 were used to calculate the minimal model noise.

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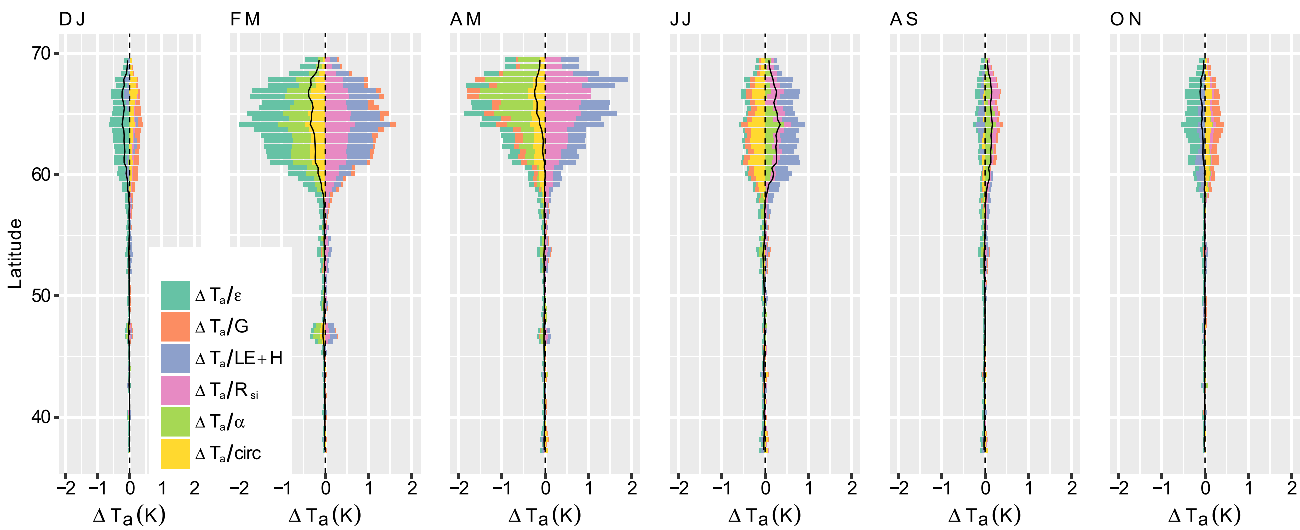

Extended Data Fig. 2 | Drivers of the mean bimonthly air temperature changes for 0.5° latitudinal bands. The notation is as in Fig. 2 and the labels at the top denote months (D J, December and January; F M, February and March; A M, April and May; and so on). Although all the components contribute to the change of the air temperature, changes in emissivity always result in cooling and changes in shortwave incoming radiation always result in warming. Consequently, emissivity and incoming shortwave radiation cannot explain the seasonal variation in air temperature changes. The other components are positively correlated with air temperature in some months and negatively correlated in others, which rules them out as the main driver of air temperature changes and suggests that the net effect is the outcome of the interplay between the different components.

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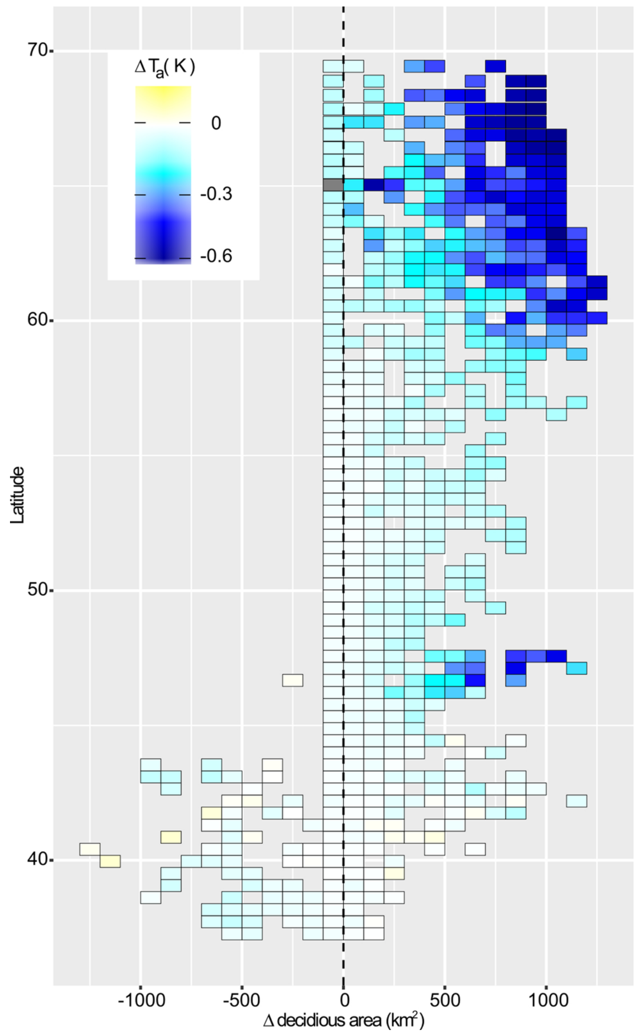

Extended Data Fig. 3 | Relationship between changes in springtime air temperature and changes in the fractional cover of deciduous forest for 0.5° latitudinal bands over Europe. Locations where the tree species are maintained between 2010 and 2100 (that is, the difference Δ of the deciduous area is 0) could experience similar air temperature changes as neighbouring locations where one tree species is replaced by another, especially in Scandinavia, suggesting advection of heat and moisture. Nevertheless, at lower latitudes the spatial scale of this advection is limited to a few pixels (for example, Fig. 2a) corresponding to a range of 50–200 km. Furthermore, the temperature effect quickly saturates with the fractional cover change and shows a strong dependence on geographical location (see Supplementary Information). Whether this apparent geographical dependence is the outcome of climatic differences or of differences between northern and southern European deciduous species could not be established with the experimental setup used in this study.

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Extended Data Table 1 | Changes in surface area of European forests by 2100 for six different forest-management portfolios

Change in surface area (km^2)	Business as usual (BAU)	Maximise carbon sink	Maximise albedo	Minimise carbon sink	Minimise albedo	Reduce near-surface temperature
Deciduous to conifers	0	475,000	30,000	6,000	516,000	41,000
Conifers to deciduous	0	266,000	590,000	236,000	26,000	534,000
Net increase conifers	0	209,000	-560,000	-230,000	490,000	-493,000
Net increase thin and fell	0	-280,000	-330,000	-390,000	-230,000	-680,000
Net increase coppice	0	-20,000	130,000	-130,000	-210,000	600,000
Net increase unmanaged	0	300,000	200,000	520,000	440,000	80,000

We note that the total surface area of forests was held constant at 2,000,000 km^2 between 2010 and 2100 for reasons described in Supplementary Information, 'Simulation experiment'.

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Extended Data Table 2 | Biogeochemical and biophysical effects over Europe in 2100 for two forest-management portfolios

Variable name (units)	Minimise carbon sink	Minimise albedo
TOA (W m^{-2})	4.32	4.32
Change in CO_2 sink & avoided emissions between 2010 and 2100(Pg C)	0.7	10.5
Change in net cumulated atmospheric CO_2 between 2010 and 2100 (Pg C)	- 0.5	- 5.7
Atmospheric CO_2 (ppm)	935.7	933.2
Near surface temperature (K)	283.85	283.86
Annual precipitation (mm)	733.1	734.2
Summer precipitation (mm)	164.0	165.4
Wood harvest (Tg C y^{-1})	122.9	176.2
Surface albedo (-)	0.119	0.107
Evapotranspiration (mm)	550.0	553.9
Latent heat (W m^{-2})	43.90	44.23
Sensible heat (W m^{-2})	27.12	26.81
Total cloud cover (%)	46.8	46.8

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